Optimized Localization for the inverting substation to maximize the braking efficiency of the DC railways

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***Abstract*—This paper presents a study to locate inverting substation(s) for the light DC railways in order to maximize the aggregated braking efficiency of the railway network. A metro line has been used in this study and it has been modeled using a railway simulator developed in MATLAB. One inverting substation unit has been installed through the metro line and its location is changed from one traction substation to another, while the corresponding aggregated braking efficiency of the metro line is calculated at each location. consequently, the localization analysis is then repeated with more than one inverting substation until the maximum aggerated braking efficiency is achieved.**

Keywords— DC railway, electrical distribution network, soft open point, braking efficiency

I. Introduction

Light DC railway networks are supplied through several traction power substation (TPSS) which are powered from one or two distribution system operators (DSO) through the medium voltage distribution networks. The majorities of such TPSS have a simple and robust design since they mainly involve transformer and diode rectifiers. However, they suffer from significant shortcoming due to the dissipation of the available regenerative braking energy of the trains in the network especially when a small number of trains travel on the line, since it cannot be fed back to the AC network due to the unidirectional behaviour of employed diode rectifiers.

Number of studies have been developed to resolve such drawback. Thyristor-based inverters are utilized instead of the diode to feed the braking energy back to the AC grid [1-2]. Moreover, IGBT inverters have also been involved in the design of the TPSS [3-4] in order to resolve the braking energy dissipation and also provide ancillary services to the AC grid [5-6].

On the other hand, energy storage systems (ESS) have also been adopted in such systems to harvest the available braking energy in the DC railway networks storage system. Supercapacitors and flywheels have been utilized in such systems as they could accept the high braking power of the train within its short braking period [7-8]. In [9], a new smart soft open point (sSOP)architecture based on power electronic converters is presented to interface electrified dc railway network with the electrical distribution networks. Considering the different dynamic characteristics of the two networks, the dc bus of the sSOP is used to connect ESS, thus allowing a decoupling of the power flows. The new inverting substations is capable of capturing the regenerative energy of rail braking and can use it to either charge the ESS, support the distribution network, or both.

This paper investigates the best location of an inverting substation in order to maximize the aggregated braking efficiency of the railway network through the different locations of the TPSS with one or more inverting substation units. the presented inverting substation in this paper is enabling the available braking energy to be fed directly back to the DSO supplying point of the TPSS under consideration. the analysis has been started with one inverting substation installed across the metro line under study and the braking efficiency has been calculated at each TPSS location. after that two inverting substations have been then installed at two different TPSS and the resultant braking efficiency is also evaluated. Accordingly, the best locations for the TPSS for installing the inverting substation units to attain the 100% braking efficiency is validated for the metro line under study.

This paper is organized as follows: Section II provides the typical architecture of the light DC railway network with the diode rectifiers units as well as with the installed inverting substation. Section III presents the employed railway simulator

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to model the metro line under study through single and multiple trains simulations. Section IV demonstrates the localization study for the inverting substation across the metro line with one or more units and evaluate the resulted aggerated braking efficiencies through a full day operation. Finally, the discussions and conclusions for the presented case study are given in Section V.

II. Light DC railway netwroks

DC traction substations are normally equipped with transformers and rectifiers, drawing electricity from internal AC distribution networks. Each traction substation is usually connected to an internal network (for example 15 kV in Spain and 11 kV in UK) owned by the metro system operator. However, due to the variability of the traction load of metro railways, the connection of this internal network to the public grid must be at a higher voltage level. Connections to the public grid are therefore made at "Grid Supply Points" and then distributed to the traction substations. The common configuration of electrical railway network with connection to DSO substation (Public Grid) is illustrated in Fig. 1. in which the inverting substation is installed parallelly with the conventional rectifier units (to enable the TPSS acts as inverter substation) so that the surplus regenerative braking energy can support loads on the MV AC network or be fed back to the DSO HV network.

III. Railway simulation platform

A railway simulator has been developed in [10] through MATLAB and utilised in this paper to represent an actual metro line network with a length of 41 km and 28 stations. The rated operating voltage of this line is 1,500 V DC. The characterisations of traction system of the train are reported in Table I. Additionally, Table II provides the parameters of the line DC electrification system.

A. Single train motion simulation

Using the data of the tables I and II and considering the speed limit on the line, the speed and power diagram of each individual train is given by Fig. 2. The trains acceleration shows the constant effort and constant power regions which are typical in the traction systems. The amount of cruising has been selected to keep the speed within the limit and guarantee that the train reaches the next station on time. In this model, there are no train delays or other causes disrupting the train service.

Moreover, it has been assumed an identical dwelling time for all the stations and all the trains. The time step of the simulation has been set to 1 second. The simulations are carried out when full service is running, i.e. excludes operations in the first hour and the last hour of the service when the number of trains is reduced.

TABLE I. Train traction characteristics

Parameters	**Value/Equation**
Overall train mass [tonnes]	180
Train formation	4 cars, M – S – R – M
Rotary allowance	0.08
Maximum acceleration rate [m/s]	1.0
Maximum braking rate [m/s]	1.0
Maximum traction power [kW]	2,400
Maximum braking power [kW]	1,800
Maximum operation speed [km/h]	80
Maximum tractive effort [kN]	170
Dwell time [seconds]	30
Auxiliary power [kW]	80

TABLE II. Power network characteristics

Parameters	**Data**
Rectifier no load voltage [V]	1650
Rectifier rated voltage [V]	1500
Rectifier rating [MW]	2 x 3.3MW
Rail track resistance [Ω/km]	0.0145
Rail resistance per 2 tracks [Ω/km]	0.00725
3^{rd} rail resistance [Ω/km]	0.0115

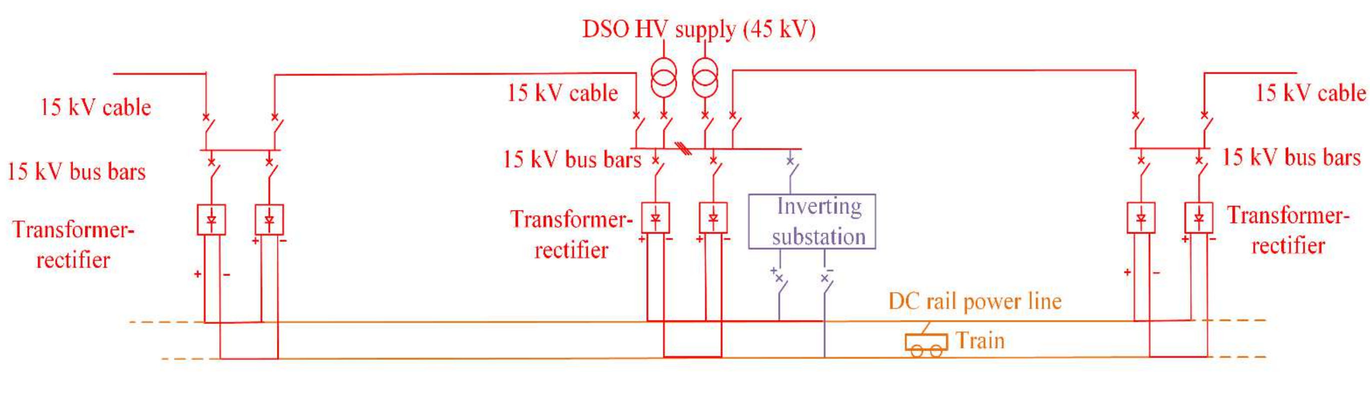

Fig. 1. *Schematic for light DC railway networks with the installed inverting substation*

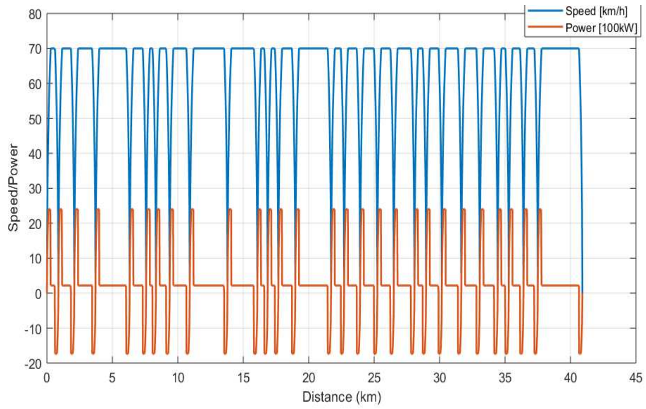

Fig. 2. *Speed and profiles of a train travelling on the network*

B. Multiple train simulation (full-day)

The trains service for the full-day operation is shown in Fig. 3 as follows:

- 36 train cycles every 6.5 mins
- 112 train cycles every 7.5 mins
- 8 train cycles every 15 mins

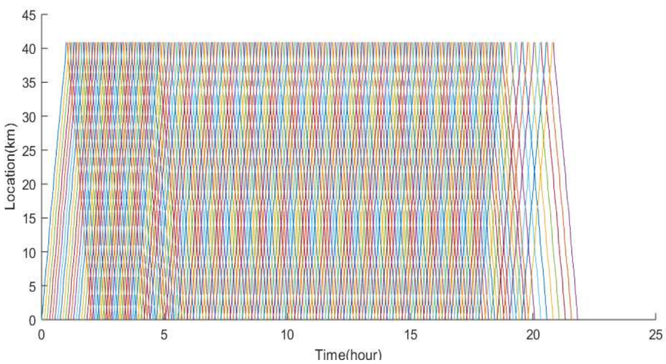

Fig. 3. *Line 12 timetable (locations of trains versus the time in a day)*

The energy consumption for a whole-day operation is shown in Table III. The total energy consumption for a day is 103.92 MWh. The trains electrical braking energy is 70.65 MWh per day. Of this electrical energy, 90.5% is reused, which is 63.95 MWh per day. The table has the following rows:

- E_s = Energy supplied by all the substations to the traction system within the headway time
- $P_{s,mean}$ = Average power supplied by all the substations within the headway time
- $E_{s,loss}$ = Energy losses of all the substations
- $E_{t,loss}$ = Energy losses of the electrification system (overhead supply and return rails)
- $E_{traction,dem}$ = Energy required by all the train to accelerate and coast
- $E_{traction}$= Energy actually drawn by all the train to complete the journey
- $E_{braking,}$ = Energy available from all the train for regenerative braking
- E_{regen} = Energy actually regenerated by trains
- η_{regen} = Efficiency of regenerative braking, calculated as $E_{regen} / E_{braking}$

TABLE III. ENERGY CONSUMPTION FOR A WHOLE-DAY OPERATION

E_s	[MWh]	103.92
$P_{s,mean}$	[MW]	5.15
$E_{s,loss}$	[MWh]	3.12
$E_{t,loss}$	[MWh]	2.37
$E_{traction,dem}$	[MWh]	134.28
$E_{traction}$	[MWh]	134.28
$E_{braking}$	[MWh]	70.65
E_{regen}	[MWh]	63.95
η_{regen}	[%]	90.5%

Table IV shows the maximum and average power for each substation for a full-day operation.

TABLE IV. TRACTION SUBSTATION POWER CONSUMPTION FROM RAILWAY SIMULATOR

TPSS	Location [m]	Maximum (MW)	Mean (MW)
1	0	2.26	0.333
2	2092	2.78	0.368
3	6320	3.53	0.425
4	9374	3.10	0.473
5	13798	2.88	0.415
6	16869	2.72	0.474
7	21712	2.87	0.497
8	25247	2.52	0.454
9	28078	2.46	0.410
10	31664	3.36	0.411
11	36412	3.37	0.458

C. Multiple train simulation (different headway time)

The system energy consumptions within the headway period are shown in Table V for various headway values, in which $P_{loss,mean}$ is the average power losses (substation and electrification) within the headway time. This refers to the energy drawn from all the TPSS during train service.

The results show that the energy consumption of the traction system increases when the headway decreases, as there are more trains running simultaneously on the line. In fact, the average power increases from 1.02 MW when the headway is 660 s to 5.16 MW when the headway is 120 s. Similar trend can be identified on power losses, but the ratio of the power losses to the respective power consumption is around 5% with various headways. The energy losses vary with the headway changes, but not significantly. When the substation energy supply is high, for example when headway is 660 s, the energy loss is higher. The substation loss is determined by the power from substation, and the transmission loss depending on the power flow in the network. The efficiency of regenerative braking decreases with the headway. In this case study, the efficiency of regeneration braking is high for this route, which is between 88% and 100%.

TABLE V. ENERGY CONSUMPTION WITH VARIOUS HEADWAYS

Headway	[s]	120	180	240	300	360	420	480	540	600	660
E_s	[kWh]	618	616	616	636	617	643	621	622	656	675
$P_{s,mean}$	[MW]	5.15	3.42	2.57	2.12	1.71	1.53	1.29	1.15	1.09	1.02
$E_{s,loss}$	[kWh]	18.5	18.5	18.5	19.1	18.5	19.3	18.6	18.7	19.7	20.3
$E_{t,loss}$	[kWh]	12.5	10.7	10.6	12.4	11.7	12.7	12.5	14.4	11.9	13.9
$P_{loss,mean}$	[MW]	0.26	0.16	0.12	0.10	0.08	0.08	0.06	0.06	0.05	0.05
$E_{traction,dem}$	[kWh]	861	861	861	861	861	861	861	861	861	861
$E_{traction}$	[kWh]	861	861	861	861	861	861	861	861	861	861
$E_{braking}$	[kWh]	453	453	453	453	453	453	453	453	453	453
E_{regen}	[kWh]	453	453	453	435	453	428	450	451	415	399
η_{regen}	[%]	100	100	100	96	100	95	99	100	92	88

IV. LOCALIZATION OF THE INVERTING SUBSTATION WITH RESPECT TO RAILWAY NETWORK

As stated in the previous section, the metro line under study has high braking efficiency especially at lower headway periods. Accordingly, this section optimises the inverting substation location at relatively high headway (7.5 min is considered at this study) to assess the benefit of the installed inverting substation unit.

Additionally, the power of the TPSSs under consideration is investigated along with the impact of the installed inverting substation in enabling energy regeneration to the distribution grid. The best location of inverting substation is evaluated by the developed railway multi-train simulation.

A. *Installation of one inverting substation*

The energy consumption has been calculated when a inverting substation is added at one of the TPSS, as shown in Table VI. The number 0 means that no inverting substation is installed (baseline case), whereas 1 means that TPSS 1 has the inverting substation and so on. Besides, $E_{s,rectified}$ refers to the rectified energy by that TPSS, while, $E_{s,inverted}$ presents the amount of energy inverted back by the installed inverting substation at this TPSS. Table VI shows that when the inverting substation is located at TPSS 4 the line achieves the lowest energy consumption. The substation energy consumption is reduced by 5.8%. from 672 kWh to 633 kWh

Furthermore, with the introduction of one inverting substation, the efficiency of regeneration is improved for all the configurations. The highest regeneration efficiency occurs when the inverting substation is located at TPSS 4, which is 98.5%, which is higher than the baseline case of 89.2%. On the other hand, the worst energy-saving performance occurs when the inverting substation is installed at TPSS 11. The regenerative energy efficiency is improved to 93.8% for this case.

B. *Installation of two inverting substations*

The energy consumption is recalculated when two inverting substations are installed at two substations. The best 10 results are shown in Table VII. These results achieve very high regeneration energy efficiency, which are equal to 99.9%. Therefore, for this line there is no need to install three inverting substations to improve the railway energy aggregated braking efficiency since the maximum efficiency has been already achieved with only two installed inverting substation units.

TABLE VI. ENERGY CONSUMPTION WITH A INVERTING SUBSTATION INSTALLED AT ONE OF THE TPSS

Location of INVERTING SUBSTATION		0	1	2	3	4	5	6	7	8	9	10	11
Headway	[s]	450	450	450	450	450	450	450	450	450	450	450	450
E_s	kWh	672	648	645	637	633	634	636	636	638	643	649	654
$E_{s,rectified}$	kWh	672	675	675	676	677	678	679	678	676	674	675	679
$E_{s,inverted}$	kWh	0.0	-26.9	-29.5	-39.5	-44.0	-44.2	-43.5	-42.3	-38.0	-31.3	-25.5	-25.3
$E_{s,loss}$	kWh	20.2	21.7	21.8	22.4	22.6	22.7	22.7	22.6	22.3	21.9	21.6	21.7
$E_{t,loss}$	kWh	16.0	18.0	18.1	17.2	16.9	16.8	16.6	16.8	17.3	18.0	18.0	17.3
$E_{traction,demand}$	kWh	861	861	861	861	861	861	861	861	861	861	861	861
$E_{traction}$	kWh	861	861	861	861	861	861	861	861	861	861	861	861
$E_{braking,available}$	kWh	453	453	453	453	453	453	453	453	453	453	453	453
E_{regen}	kWh	404	431	435	443	446	445	443	443	441	437	430	425
η_{regen}	%	89.2%	95.2%	96.0%	97.7%	98.5%	98.3%	97.9%	97.9%	97.4%	96.5%	95.0%	93.8%

TABLE VII. ENERGY CONSUMPTION WITH A INVERTING SUBSTATION INSTALLED AT TWO INVERTERING SUBSTATIONS OF THE TPSS

location of inverting substation 1		0	4	3	4	3	4	3	4	3	4	2
location of inverting substation 2		0	7	7	8	6	9	8	6	5	5	5
Headway	[s]	450	450	450	450	450	450	450	450	450	450	450
E_s	kWh	672	627	627	627	627	627	627	627	628	628	628
$E_{s,rectified}$	kWh	672	682	682	681	682	679	680	682	680	680	680
$E_{s,inverted}$	kWh	0.0	-55	-55	-54	-55	-52	-53	-54	-52	-52	-52
$E_{s,loss}$	kWh	20.2	23	23	23	23	23	23	23	23	23	23
$E_{t,loss}$	kWh	16.0	16	16	16	16	17	17	16	16	16	17
$E_{traction,demand}$	kWh	861	861	861	861	861	861	861	861	861	861	861
$E_{traction}$	kWh	861	861	861	861	861	861	861	861	861	861	861
$E_{braking,available}$	kWh	453	453	453	453	453	453	453	453	453	453	453
E_{regen}	kWh	404	452	453	453	452	453	452	452	451	451	452
η_{regen}	%	89.2%	99.9%	99.9%	99.9%	99.8%	99.9%	99.9%	99.7%	99.7%	99.6%	99.7%

V. CONCLUSIONS

From the presented case study in this paper, installing the inverting substation in the DC light railway networks can improve the recuperation of the regenerative braking energy from their trains and accordingly reduce the overall substation energy consumption. A railway simulator has been employed to model a real DC metro network. The single and multiple train simulations have been applied to the line under study to estimate the energy consumption for a whole-day operation at different headways periods. Moreover, the best location for installing the inverting substation has been investigated. It has been shown that a single inverting substation located at TPSS 4 achieves a maximum of energy recuperation of 93.8%, which is a reduction of 5.8% below the baseline condition. TPSS 4 attains the highest regenerative braking efficiency since it provides the highest E_{regen} (of 446 kWh) among the other TPSSs. This outcome is mainly dependant of the specifications of the metro line under study as well as the selected trains' timetable. On the other hand, by installing two inverting substations at two different TPSSs the highest high regeneration energy efficiency 99.9% is achieved at several situations with a reduction of 6.7% in the total energy consumption from the baseline situation. As a result, there is no need to install inverting substations at all the traction power substation, but a suitable choice of the location is sufficient to maximise the railway energy aggregated braking efficiency for the line.

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